# Existence and Use of Low-Pollution Route Options for Observed Bicycling Trips

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**Do routes with lower doses of air pollution exist in real-world bicycling networks, and do bicyclists actually use those routes? Low-pollution-dose alternative routes for a sample of urban cycling trips were modeled and compared with shortest paths. Bicyclists' actual route choices on the same trips were observed with the use of GPS data and compared with the low-dose and shortest paths alternatives. With use of past studies of pollution exposure levels and simplified ventilation rates, link-inhaled doses of air pollution were estimated. Findings suggest that a majority of trips have lower-dose alternatives to the shortest path, with a 12% average dose reduction. Cyclists tend to choose routes with pollution concentrations between those of shortest paths and minimum-dose routes, but they also travel considerably farther, leading to total inhaled doses that are higher than on either alternative route. People's seeming avoidance of nontraffic factors such as hills, excess turns, and difficult intersections leads to longer than optimal detours from a pollution avoidance perspective. Bike paths and bike boulevards (traffic-calmed streets with bicycle priority), as well as denser street grids, appear to provide effective low-pollution alternatives, although such routes tend to encourage excess detours that can add to total inhaled dose. Bike lanes can draw cyclists onto more polluted routes in some circumstances, with poor pollution inhalation outcomes. Overall, excess doses did seem to be a common problem for this sample of cyclists on a real-world network. The study's findings support policies that provide dense networks of attractive facilities that encourage cyclists to choose direct, lower-pollution routes.**

Bicycling is rightly promoted as a travel mode that addresses a raft of urban planning issues. In a recent report, FHWA suggested that, in addition to ongoing traffic congestion and air quality concerns, increased bicycling has the potential to improve or mitigate growing problems of public health, greenhouse gas emissions and energy use, aging populations, and community livability (*1*). At the same time, increased bicycling brings new planning challenges of its own. In particular, bicyclists are more exposed to elements of the travel environment along the way, including the risk of collision with motor vehicles and breathing polluted air along roadways. Understanding, measuring, and planning to reduce such risks is increasingly important to realizing the full potential of urban bicycle policy.

Long-term exposure to traffic-related air pollution is associated with increased mortality (*2*), while short-term exposure during travel has been shown to have acute health effects (*3*). The long-term health outcomes of daily travel-related exposure specifically have not been established; however, health impact assessments usually assume that changes in pollution inhalation during regular (commuting) travel, as a percentage of daily inhalation, have effects comparable with proportional changes in long-term exposure levels (*4–6*). Given the current state of knowledge, then, bicyclists' routes that minimize pollution inhalation would be expected also to minimize the pollution-related health risks of daily bicycling.

A large literature has established that bicyclists make choices on the basis of the travel environments available to them. In particular, in addition to minimizing distance and delays, research has shown that cyclists choose routes on the basis of a range of factors, including a preference for lower-traffic and off-street facilities (*7–11*). Use of lower-traffic and off-street paths can reduce air pollution exposure for urban bicyclists (*12*). If a route with lower exposure takes a cyclist too far out of his or her way, however, the longer time spent breathing a lower pollution level may actually increase the total amount of pollution inhaled.

In previous research, theoretical distance and exposure trade-offs were compared. It was found that, on the basis of existing estimates of route preferences, cyclists tended to choose routes that approximately minimized traffic-related pollution inhalation dose when they detoured to use off-street paths, bike boulevards, and low-to-moderate traffic streets with or without bike lanes (*13*). In other words, it appeared that cyclists would in general detour far enough to avoid traffic (and related pollution) without going so far out of their way that the extra duration of exposure would outweigh the reduced pollution levels. When it came to high-traffic streets, however, it was found that bicyclists might tend to choose more direct, busy streets too often if those streets had a bike lane and not often enough if there was no bike lane, from the perspective of minimizing pollution inhalation.

In this research, previous theoretical work on route choice preferences and pollution exposure was extended to consider actual behavior on real travel networks. The most similar prior work was done in Montreal, Canada, comparing minimum pollution exposure routes versus shortest distance network paths (*14*). The study used the actual travel network and origin–destination pairs from a survey of cycling trips, finding that route alternatives with lower pollution exposure existed for 57% of the sampled trips. Neither actual traveled routes nor route preferences were part of the study, so willingness to detour to low-exposure routes was not addressed. In reality, observed bicyclists' routes commonly deviate from the shortest path, with mean reported distance deviations of 7% to 12% (*7, 11, 15*).

Using GPS data, researchers added observed cycling routes to the comparison of shortest paths and minimum-dose routes (MDRs). As far as was known, observed network paths have not been considered in comparisons with pollution-minimizing behavior. Researchers

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also made an initial attempt to acknowledge the potential for inhalation rates to vary across cyclists. The goal of this work was to improve understanding of the air-pollution-risk implications of bicycle route preferences as they are realized in a real-world travel network; this information is potentially important to the health-conscious design of bicycle networks and bicycle route guidance. The primary research questions follow: (*a*) What is the prevalence and magnitude of low-dose alternatives to shortest paths in a real urban street network? (*b*) How do bicyclists' chosen routes compare with low-pollution alternatives? and (*c*) What factors, network or personal, affect the likelihood of higher or lower pollution doses on cycling routes? These research questions were addressed by comparing shortest paths, MDRs (considering both concentration and time), and observed routes. Whether and where excess pollution doses are likely to occur will be discussed, as will policy options in the light of the findings. Future work will consider additional dimensions that were too complex to address at this time, including the impacts of hills, intersections, and detailed modeling of cyclists' speed and ventilation rates.

## METHOD

The basic method consisted of four main modeling steps along with several simplifying assumptions. First, observed routes were extracted from raw GPS data and taken as a reflection of cyclist route preferences. Second, a simple model of pollution inhalation dose at the network link (intersection to intersection) level was developed on the basis of presumed differences in on-road pollution sources, ignoring other potential differences caused by near-road sources, topography, weather, and so on, and taking travel speed and ventilation rates as fixed for each person. The link-level inhaled dose estimates were then used to define a single MDR from trip origin to destination. Finally, the three network paths—shortest, observed, and dose minimizing—were compared for each case, examining overlap and differences among a range of factors. The remainder of this section describes each step and supporting data in more detail.

### GPS Observed Route Data and Geographic Information System Travel Network

Observed cycling behavior was drawn from GPS data collected in 2007 by 164 adult bicyclists who were recruited using a variety of nonrandom methods from throughout the Portland, Oregon, metropolitan region (*16*). The participants were primarily experienced cyclists who reported riding weekly throughout the year; female cyclists were intentionally oversampled in the study design. Participants were outfitted with small handheld GPS devices that they clipped onto their bicycles. The devices were programmed for the participant to enter both weather and trip purpose at the beginning of each trip and to indicate whether the bicycle was being taken on transit or another motor vehicle. The device recorded its location every three seconds. The cyclists also completed a survey questionnaire that included basic demographic information including height, weight, and age.

The geographic information system travel network developed for this research included 127,915 undirected links and 100,857 nodes. This network was constructed to include all facilities available for bicycle travel insofar as possible. Included were a large number of links not usually found in an automobile travel modeling network, including minor residential streets, off-street bike and multiuse paths, alleyways, and some private roads explicitly open to bicycles.

Network attributes included bicycle facilities and average daily traffic (ADT) on each link. Bike lanes refer here to bicycle-only lanes designated with painted stripes and immediately adjacent to motorized traffic. Bicycle boulevards (or bike boulevards), sometimes called neighborhood greenways, are streets that have been treated to reduce and slow traffic, with bicycles given priority through traffic diverters, bicycle-only movements, "flipped" stop signs that give the boulevard the right of way at minor intersections, and bicycle-activated signals at major intersections. There is evidence that bike boulevards are preferred to both regular residential streets and bike lanes (*7, 17*). A multiuse path refers to any off-street facility, either adjacent to a street or in a more park-like setting.

Count-based traffic volumes were provided by the City of Portland for all network links in the city using standard interpolation methods applied to nearby counts where primary counts were not available. For travel outside the city boundaries, estimated traffic volumes were calculated from a functional class-based regression equation.

### Route Analysis

Observed routes were extracted from the raw GPS data by first applying a trip-splitting algorithm and then matching the resulting trip points to the geographic information system travel network. Points for each person were transformed into trip stages (single-mode trip segments) by adapting existing GPS processing algorithms (*18*). Although participants were instructed to start a new trip each time an intermediate destination was reached, they often either forgot to do so or did not understand when to split their travel into trips.

Once points were assigned to trip stages, a multiple hypothesis map matching technique was adapted from existing work and applied to each series of trip stages (*19*). Map matching is the process of assigning a series of GPS points to network links (street segments between intersection nodes). The multiple hypothesis method makes use of network topology to ensure that only feasible routes are chosen, in contrast to proximity-based algorithms, which may match to nonsensical routes (e.g., jumping back and forth between the lower and upper decks of a bridge). The existing method was modified to include an additional step of "snapping" points to network links, so that subsequent calculations, such as the slope between points, could be made along the network, rather than the raw point locations, which are subject to well-known positional errors. The method also produces fit statistics, including an average match score and number of "odd" links, with recommendations for screening criteria. Slightly stricter versions of the original criteria were used to eliminate trips matched to suspect routes. An additional rule was added, that matched route network distance should fall within 10% of the point-to-point distance estimated from GPS points. Although trip stages were actually used for all further analysis, trip stages and trips will be referred to interchangeably. Once routes were map matched, route-level statistics were calculated on the basis of traversed link attributes.

Comparable shortest path routes were calculated in the usual way by minimizing the sum of link lengths between each trip origin and destination. The minimum-dose path was calculated as the network path that minimized the sum of calculated link-level pollution inhalation between each trip's start and end points. The calculation of each link's inhaled dose itself is more complicated and is described in the following subsection.

### Calculation of Link-Inhaled Dose

The pollution inhalation dose ($I$) over route segment $s$ ($I_s$ in μg) was calculated as

$$I_s = \frac{1}{6 \times 10^4} \frac{l}{v} C \dot{V}_E \tag{1}$$

where

$l$ = segment length (m),
$v$ = average travel speed (m/s),
$C$ = pollutant concentration in breathing zone air (μg/m$^3$), and
$\dot{V}_E$ is ventilation rate (L/min).

Route total inhalation dose $I$ was calculated for observed and alternate routes, each of which comprised a set of route segments $s$, as

$$I = \sum_s I_s = \frac{1}{6 \times 10^4} \sum_s \left( \frac{l}{v} C \dot{V}_E \right)_s \tag{2}$$

Applying Equation 2 requires information about $v$ on both observed and alternative routes—the latter of which lack observational data. Modeling segment-level bicycle speeds is a nontrivial task, and one without validated methods in the literature. To simplify the route comparison, this analysis assumes person-specific fixed bicycle speeds, independent of route characteristics and assigned on the basis of observational data.

Ventilation rate $\dot{V}_E$ depends on (dynamic) $v$, road grade, and fixed personal factors (physiology, mass, equipment, and so on), with additional (stochastic) influences leading to relatively minor intraperson variation (*20*). Similar to $v$, because of the difficulty of predicting $\dot{V}_E$ on unobserved routes, the route comparison was simplified by assuming person-specific fixed $\dot{V}_E$ during bicycling (modeled for observed routes), independent of route characteristics. The limitations of this assumption, particularly as it relates to hills, are the subject of planned future research. With person-specific fixed $v$ and $\dot{V}_E$, a ventilation rate per unit distance (in L/m) is calculated as follows:

$$\dot{V}_d = \frac{1}{60} \frac{\dot{V}_E}{v}$$

The route inhalation dose can then be calculated:

$$I = \frac{\dot{V}_d}{1{,}000} \sum_s (l \cdot C)_s$$

Modeled in this way, proportional differences in inhalation among route alternatives for a trip are independent of $\dot{V}_d$ and are entirely derived from segment length and concentration levels ($l$ and $C$). Still, $\dot{V}_d$ is estimated to compare the $I$ differences among routes with the interpersonal differences. Segment length $l$ is easily drawn from the network data. The next subsections describe the modeling of $C$ and $\dot{V}_d$.

#### *Concentrations*

Exposure concentrations are determined by a number of route attributes, including traffic volume and composition, intersections and major road crossings, distance to major roads, bicycle facility type, and near-road sources, as well as nonroute conditions such as background concentrations and weather (*12*). To simplify this initial analysis, only facility-related exposure differences were considered, factors such as those related to background levels, weather, topography, and nonroad sources. As described in earlier work, exposure on network links is considered a function of whether a link is separated or on-street, and, for on-street facilities, ADT is included (*13*):

$$C = \exp(\beta_0 + \beta_1 * \text{path} + \beta_2 * \text{OnRoad} + \beta_3 * \text{ADT})$$

To reduce the number of parameters, researchers focused on proportional differences among route alternatives. Thus, it was possible to normalize concentrations to off-street path exposure (expected to be the lowest) and simplify to the following:

$$C_{\text{rel}} = \exp(\beta_2 * \text{OnRoad} + \beta_3 * \text{ADT})$$

where $C_{\text{rel}}$ is relative concentration.

Existing literature reporting bicyclist on-road measured exposure concentrations, as summarized in previous work (*13*) and supported by more recent studies (*21, 22*), implies the following values for typical traffic volume and on-road concentration effects:

- +2% per 1,000 ADT: $\beta_3 = 0.00002$ and
- ~30% higher on-road, in addition to the ADT effect: $\beta_2 = 0.26$.

These parameter estimates represent the more strongly traffic-related pollutants such as carbon monoxide, certain volatile organic compounds, and black carbon and ultrafine particulate matter. Sensitivity analysis was undertaken, using $\beta_3$ of 0.00001 to 0.00003 and $\beta_2$ of 0.0 to 0.4, on the basis of the same sources.

To summarize, link exposure levels are either

- Off-street paths: $C_{\text{rel}} = 1$ or
- "OnRoad," including mixed traffic (any facility with ADT > 0), painted bike lanes, and bike boulevards: $C_{\text{rel}} = \exp(\beta_2 + \beta_3 * \text{ADT})$.

Separated cycle tracks (bicycle-specific travel lanes that are in the roadway but separated from moving traffic by either parked cars or fixed barriers) were not present in the network at the time of data collection.

#### *Ventilation*

Power output during bicycling ($P$ in watts) was calculated from observed trip data (3-s speed and road grade) by using well-validated physical models (*23–25*):

$$P = \max\left((m + m_b) v [g(G + C_R) + a] + 0.5 \rho C_D A_F v^3, 0\right)$$

where

$a$ = acceleration (m/s$^2$),
$m$ = rider mass (kg),
$m_b$ = bicycle mass (kg),
$g$ = gravitational constant (9.81 m/s$^2$),
$G$ = road grade (unitless),
$C_R$ = coefficient of rolling resistance (unitless),
$\rho$ = air density (1.23 kg/m$^3$),
$C_D$ = drag coefficient (unitless), and
$A_F$ = frontal area (m$^2$).

The bicycle power parameters $C_R$, $A_F$, and $C_D$ were sampled from normal distributions with means of 0.004, 0.6, and 1.0, and standard deviations of 0.001, 0.1, and 0.1, respectively (*20, 23, 25–28*). The bicycle mass $m_b$ was sampled from a uniform distribution of 10% to 30% of *m,* on the basis of Bigazzi and Figliozzi (*20*) and Wilson (*25*); however, $m_b$ (including cargo) could vary greatly for different types of bicyclists, and more research is needed to characterize all of these parameters for utilitarian bicyclists.

$\dot{V}_E$ during bicycling was modeled as

$$\dot{V}_E = \exp\left(\alpha + \beta \ln\left(2 \cdot \text{RMR} + 0.011 \cdot P\right)\right)$$

where

$\alpha$ and $\beta$ = parameters that depend on age and sex,
RMR = resting metabolic rate in l $O_2$/min, and
$P$ = trip-mean power output of the bicyclist (W) (*29, 30*).

Trip mean was used to model $\dot{V}_E$ to avoid the dynamic ventilatory response observed with higher-resolution power data (*20*). Age-specific values for $\alpha$ and $\beta$ were taken from EPA (*30*); RMR was taken from Schofield (*31*) and converted to the units of $\dot{V}O_2$ (L $O_2$/min) by using an individual oxygen conversion efficiency *H* (in L $O_2$ per kcal) sampled from uniform distributions of 0.19 to 0.20 for females and 0.20 to 0.22 for males (*30*).

Person-average *v, P,* and $\dot{V}_E$ were calculated as the means of trip-average values, weighted by trip duration. To summarize, participant (weight, age, sex, height) and travel (speed and road grade) data from the GPS study were combined with parameter values that were assumed on the basis of the literature (primarily $C_R$, $A_F$, $C_D$, $m_b$) and established models to determine person-average $\dot{V}_d$ (and *P,* $\dot{V}_E$, *v*).

## RESULTS

Table 1 presents summary statistics from the route analysis of 1,320 trips by 146 people. Person-specific demographic and ventilation data were available for 73% of trips (the others used the mean $\dot{V}_d$ = 0.171 l/m). $\dot{V}_d$ has somewhat less variation than $\dot{V}_E$ because it is moderated by speed: $\dot{V}_d$ has an interquartile range (IQR) of 34% of the median value, while for $\dot{V}_E$ it is 47% of the median. Figure 1 provides an example of a trip with three distinct routes. Figure 2 summarizes results for each route type graphically.

**TABLE 1 Summary Statistics**

| Variable | Median | IQR |
|---|---|---|
| People, $n$ = 146 | | |
| $v$ (km/h) | 18.0 | 15.3–20.2 |
| $p$ (W) | 103 | 78.5–131 |
| $V_E$ (l/min) | 47.7 | 37.3–59.8 |
| $V_d$ (l/m) | 0.161 | 0.137–0.192 |
| Trip length, $n$ = 1,320 (km) | | |
| Shortest | 2.74 | 1.01–5.02 |
| Minimum dose | 2.89 | 1.02–5.26 |
| Observed | 3.04 | 1.12–5.83 |
| Trip average concentration, normalized to off-street path | | |
| Shortest | 1.48 | 1.36–1.67 |
| Minimum dose | 1.35 | 1.31–1.40 |
| Observed | 1.41 | 1.34–1.53 |
| Trip inhaled dose (off-street path concentration * $m^3$) | | |
| Shortest | 0.629 | 0.229–1.34 |
| Minimum dose | 0.593 | 0.225–1.16 |
| Observed | 0.671 | 0.260–1.34 |

NOTE: IQR = interquartile range.

With a practical threshold of at least 1% difference in pollution dose, 62% of trips had available lower-dose detours from the shortest path. Detours on average had a 12% lower dose (IQR: 4% to 17%), up to a maximum of 56% lower. The average minimum dose alternative had 16% lower concentrations (IQR: 6% to 23% lower) and had 6% longer distance (IQR: 1% to 8% longer). A univariate binary logistic regression model for the existence of a lower-dose detour was also estimated. On the basis of the estimation, each additional 100 m in the shortest path increases the likelihood of a lower-dose detour existing by 9% ($p$ < .01). Each additional link in the shortest path

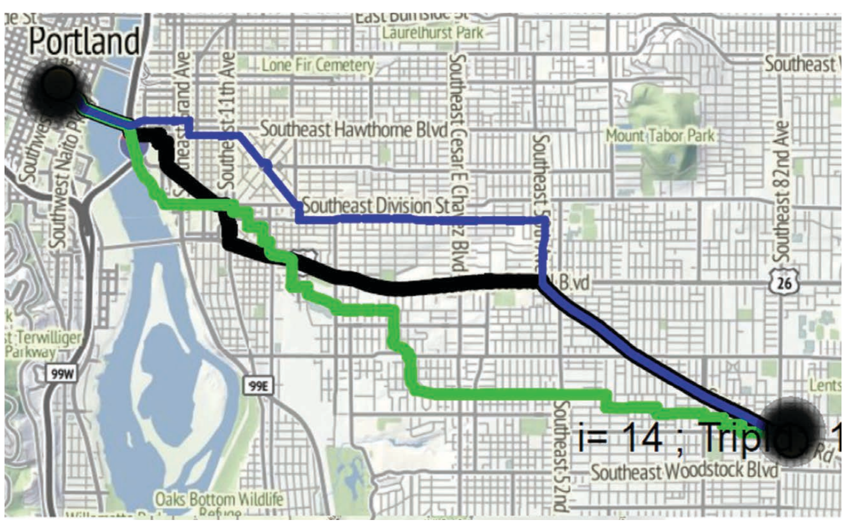


FIGURE 1 Example of minimum-dose route (green), shortest path (black), and observed route (blue).

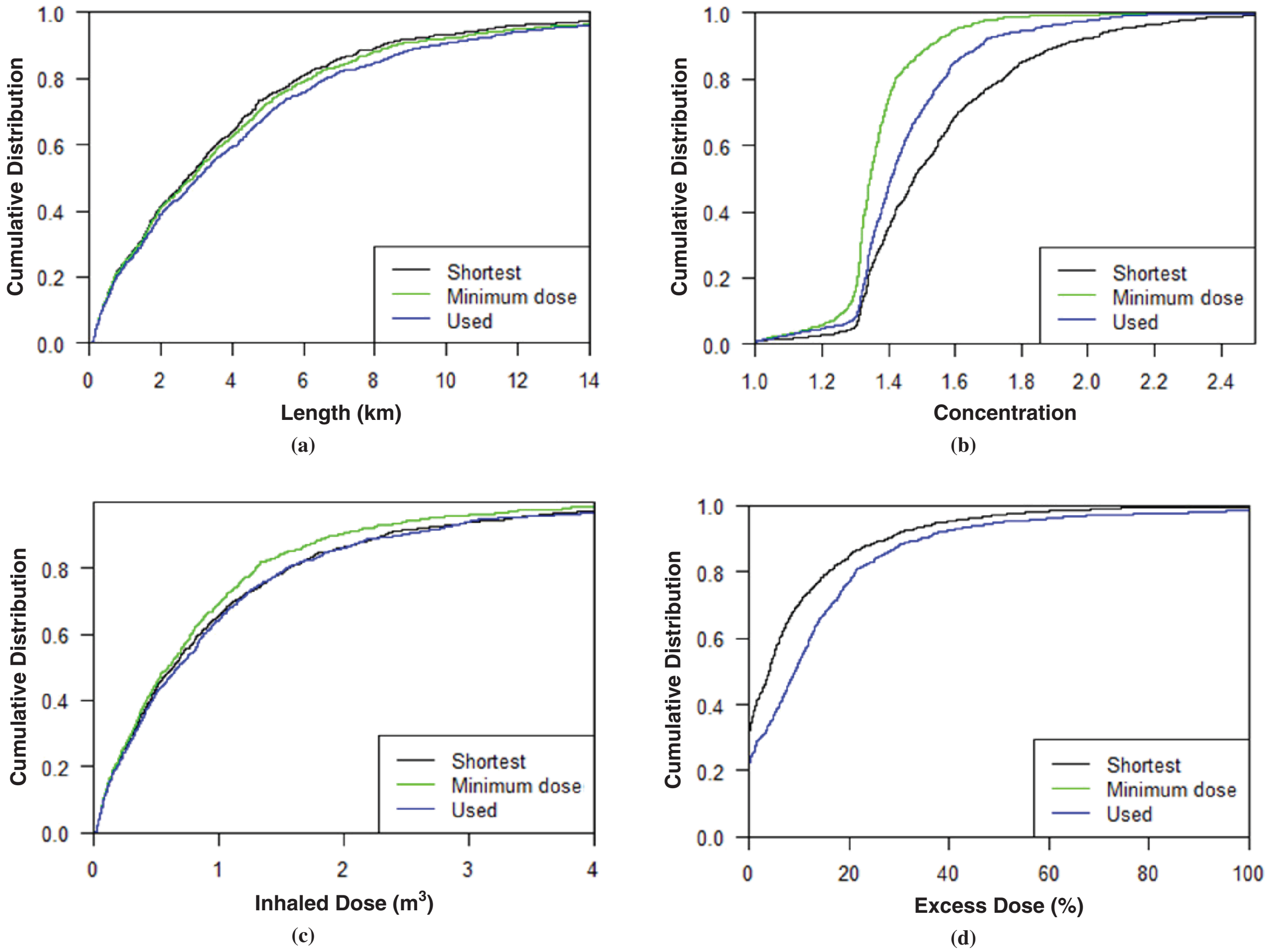


FIGURE 2 Cumulative distributions of (*a*) route lengths, (*b*) concentrations normalized to off-street paths, (*c*) inhaled doses normalized to off-street paths, and (*d*) excess dose compared with minimum-dose route.

increases the likelihood of a lower-dose detour existing by 15% ($p < .01$) and is a better predictor than length, according to the Akaike information criterion. This finding is consistent with the idea that networks with higher intersection densities offer better options for traffic and traffic-related pollution avoidance.

For observed deviations from the shortest path—again with a threshold of at least 1% difference—66% of trips deviated from the shortest path, by an average of 14% (IQR: 6% to 18%). This is largely consistent with other GPS-based data sets, though it is on the higher end of those estimates (*15, 32*). Part of the difference may be because of some unusually long detours, clearly influenced by other factors besides primarily accomplishing the trip but not always labeled as exercise. Eleven trips were more than three times longer than the shortest path (< 1% of trips), and these were removed from further analysis.

Finally, attention was turned to observed versus minimum-dose routes. Observed routes were frequently longer than the shortest path, but also tended to be longer than the minimum-dose detours, on average 9% longer (IQR: 0% to 10% longer). Concentrations on cycled routes were lower than on shortest paths but higher than on minimum-dose routes, falling roughly midway between shortest and minimum-dose routes; on average, concentrations were 6% higher than on the minimum-dose route (IQR: 0% to 9%) and 5% lower than on the shortest path (IQR: 0% to 9%). Combining these effects, inhaled doses were higher than on minimum-dose or shortest-path routes—on average, 15% higher than on the minimum-dose route (IQR: 1% to 19%) and 6% higher than on the shortest-path route (IQR: 0% to 9%). In other words, cyclists were observed to be detouring so far that the additional duration of exposure more than offset the lower concentrations of pollutants along the chosen routes. People seem to be partially detouring to avoid exposure to traffic (and possibly traffic-related air pollution); however, the excessive detouring was likely not because of an overavoidance of traffic but because of avoidance of other factors such as hills, intersections, or turns.

Table 2 summarizes observed routes and comparisons with the minimum-dose route as well as each of the three route types individually. On the basis of exposure and duration deviations from the minimum-dose route:

- 26% used the MDR (either the MDR, or within 1% of minimum dose),
- 10% underdetoured compared with the MDR (higher concentration, shorter route),
- 15% overdetoured compared with the MDR (lower concentration, longer route), and
- 49% chose a dominated route, from a pollution-dose perspective (both higher concentration and longer route); it was assumed that this choice was motivated by other factors.

**TABLE 2 Summary of Cycling Routes**

| Route Type | Turns per Kilometer | Mean Elevation Gain (%) | Mean ADT | Route with Bike Facilities[a] (%) | | | Overlap Between Routes[b] (%) | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Multiuse Path | Bike Boulevard | Bike Lane | Used and MDR | Used and SP | MDR and SP |
| MDR, 337 trips | 2.9 | 1.6 | 4,300 | 7.6 | 5.6 | 12.6 | 94 | 91 | 89 |
| Underdetour, 135 trips | 1.4 | 1.1 | 12,300 | 3.2 | 7.2 | 38.5 | 30 | 70 | 29 |
| Overdetour, 200 trips | 2.9 | 1.0 | 2,900 | 15.7 | 11.4 | 11.5 | 40 | 31 | 63 |
| Dominated, 637 trips | 2.3 | 1.1 | 5,900 | 6.8 | 13.9 | 22.4 | 29 | 31 | 43 |
| All used | 2.5 | 1.2 | 5,700 | 8.0 | 10.7 | 19.9 | 48 | 51 | 57 |
| All SP | 2.5 | 1.3 | 8,200 | 5.7 | 5.1 | 17.9 | | | |
| All MDR | 3.0 | 1.3 | 3,300 | 8.6 | 6.2 | 9.6 | | | |

NOTE: SP = shortest path.
[a]All other facilities are mixed-traffic.
[b]Computed as mean percentage of links in each route that are also in the other route.

Examining the differences in route attributes across route types suggests some reasons cyclists may have chosen alternatives with poor pollution inhalation outcomes. Minimum-dose routes require about 0.5 turns per kilometer in excess of shortest path routes. It was observed that when cyclists deviated from the minimum-dose route, they encountered considerably less elevation gain. Research has found cyclists are relatively sensitive to both grades and excess turn frequency (*7*). As expected, cyclists who underdetour or overdetour are using routes with more or less traffic, respectively. In general, people are most likely to follow the MDR when it corresponds to the shortest path—as one would expect—and underdetouring seems to be largely a result of sticking to the shortest path.

In terms of specific bicycle facility types, results are mixed. Cycling on multiuse paths is associated with overdetours, while bike boulevards are associated most often with dominated and overdetoured trips. Bike lanes are most commonly used as part of underdetoured and dominated routes. Although people might deviate from minimum-dose alternatives to use them, multiuse paths and bike boulevards are effective in providing low-exposure routes that people actually seek out and use. In univariate regression, the percentage of shortest paths on multiuse paths and bike boulevards is significantly ($p < .01$) associated with lower concentrations on the used route. Conversely, the percentage of shortest paths with bike lanes is significantly ($p < .01$) associated with higher concentrations on the used route. Consistent with past research on route choice, when bicycle-specific infrastructure is both available and reasonably direct, cyclists will use it. For multiuse paths and bike boulevards, this can have a positive impact on pollution inhalation by leading cyclists toward lower concentrations, as long as the added duration is not too great. Bike lanes, on the other hand, tend to lead cyclists toward higher concentrations because of their placement primarily along arterial streets. Broach et al. reported that bike lanes appeared to completely offset the perceived cost of riding on high-traffic roads (*7*), and the present analysis seems to bear that out, with poor outcomes for pollution inhalation.

Researchers also considered whether route connectivity and street density had impacts separate from bicycle-specific facilities. The number of links within a 1-km buffer of the trip origin was calculated as a rough and ready metric, and relationships to pollution avoidance were tested with simple univariate regressions. Results were mixed. There was a positive effect on both the likelihood that a lower-dose detour from the shortest path existed [odds ratio (OR): 1.009, $p < .01$] and that the observed route exceeded the minimum dose (OR: 1.010, $p < .01$). However, as noted earlier, much of the observed variation is caused by chosen routes' excess length (likely influenced by other factors); so in terms of concentrations only, link density near the origin was both

- Significantly associated with the likelihood that the observed route had lower concentrations than the shortest path (OR: 1.007, $p < .01$) and
- Significantly associated ($p < .01$) with lower concentrations on minimum-dose routes and observed routes, but not on shortest path routes ($p = .97$).

In short, denser street networks appear to create more opportunities for minimum-dose routing, and lead to lower-exposure route choices (though these are still longer than the minimum-dose route).

Route comparisons were also made with varying concentration parameters $\beta_2$ and $\beta_3$ to represent different contexts and pollutants. High and low parameter values represent more and less, respectively, pollutant spatial heterogeneity and concentration around roadways. With low parameter values, MDRs deviate less from the shortest path and yield smaller dose reductions, and there is a shift toward overdetouring in the observed routes (from 15% to 32%). Conversely, with high parameter values, MDRs deviate more from the shortest path and yield larger dose reductions, and there is a shift toward underdetouring in the observed routes (from 10% to 16%). Because motor vehicle traffic generates many pollutants with varying levels of spatial heterogeneity, there is expected to be, in some cases, no single minimum-dose route for all pollutants; some observed routes will overdetour for one pollutant but underdetour for another.

Finally, the influence of person-specific ventilation rates was considered, for only the trips with survey data available. Most analysis is proportional, so this was not a major influence on results. No significant ($p > .10$) association was found between $\dot{V}_d$ and excess dose or the likelihood of a non-minimum-dose route choice, so it does not appear that higher-ventilation (per meter) riders are systematically more likely to experience excess doses. However, there are significant ($p < .01$) positive associations between $\dot{V}_E$ and the likelihood of a non-minimum-dose route choice (OR: 1.057) and the amount of excess dose, so it does appear that higher-power riders are more likely to choose non-minimum-dose routes. This effect persists if trips made for the purpose of exercise are removed. These results should be interpreted with caution, because hills and stops were not included in the analysis—that is a major next step.

## CONCLUSIONS

The primary motivation of this research was to extend previous theoretical work on cyclists' route choice preferences and pollution doses to real cyclists on actual networks (*13*). In general, the speculative work was validated by real-world behavior. Results confirmed that people are detouring from shortest paths to lower-exposure routes. Most trips exceed minimum doses, however, and there are many "dominated" route choices from a pollution dose perspective, likely because of other factors influencing route choice, such as turns and grades. As predicted, underdetouring is associated with the use of bike lanes and higher traffic volumes; overdetouring is associated with multiuse paths and bike boulevards. Dense networks do tend to provide more opportunities for low-dose routes and are associated with lower exposure levels on used routes. Multiuse paths and bike boulevards along shortest paths are associated with lower exposure on routes cyclists actually use.

The results are also consistent with other existing studies of excess pollution doses and cycling in Montreal, Canada, and Copenhagen, Denmark, which did not include actual routes (*14, 33*). The findings agree with the percentage of routes with lower-dose detours, and the magnitudes that were found were in between the other two studies for concentration, distance, and total exposure differences.

Some limitations to this approach remain, even after incorporation of actual cycling behavior and travel networks. Some factors that are known to be important for route preference, duration, and ventilation rates had to be left out, including the impacts of hills, intersections, turns, high-traffic route crossings, and, in general, a more nuanced accounting of speed variation. In future extensions of this work, ventilation–power–speed interactions will be investigated in more detail, with speed modeling incorporated, leading to simulated power on alternative routes. In addition, little is known about whether and how bicyclists incorporate pollution avoidance into route decisions, but this is obviously of interest here. Air pollution is strongly correlated with other traffic effects such as crash risk, noise, and stress, and research to disentangle these factors for route choices would be useful, including whether providing information about pollution would modify behavior. Finally, it is also worth noting that policies that reduce traffic volumes or related pollution levels would change the results and reflect an alternative or complementary approach to diverting cyclists from busy routes.

The more policy-oriented question is, are excess doses a problem (in Portland)? To some extent, yes, they are. On average, pollution doses on cycled routes are 15% higher than on the MDR available. People are avoiding high-traffic, high-exposure links, but they could do so even more, yielding an additional 6% exposure reduction. Excess duration is potentially less of a concern, because there are likely offsetting health benefits from the additional physical activity. It is also an issue that 62% of trips have to detour from their shortest path to reduce pollution inhalation, although the magnitude was fairly small (6% longer). Ideally, a bike network would provide direct and low-exposure route options. Off-street paths, bike boulevards, and dense networks are associated with lower exposure levels on observed routes, although they should ideally be pervasive enough to not require large ("over") detours. Bike lanes on arterials can be problematic for pollution exposure, even as they provide more attractive, direct routes for many cyclists. There should also be attractive low-exposure options nearby, so that more time-sensitive cyclists have low pollution routes that work for them. Bicycling is a wonderful activity for the health of urban people and places, but that does not mean that it cannot be made even better and healthier for all involved.

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